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## SENSITIVITY ANALYSIS WITH A SIMPLE CHARGING CODE

by

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G. L. Wrenn



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## SUMMARY

Computer simulation techniques using codes such as NASCAP have proved very successful in tackling the spacecraft charging problem. Although a full dynamic three-dimensional code is required to model a spacecraft in orbit, simpler codes (*eg* MATCHG) can do much to clarify the interaction between the environment and a surface. It is difficult to obtain complete data on either the incident particle fluxes or the material properties which determine the various current components. The latter are dependent upon particle energy which is in turn a function of surface potential; therefore the resulting equilibrium and the charging time to attain this potential are controlled by a long list of input parameters. In order to assess the sensitivity of a solution to each of these inputs, a simple code (EQUIPOT) is used to calculate the net current as surface potential is stepped from zero to that required for equilibrium, (Jnet = 0). The required accuracy for all the parameters is then established by successively introducing a delta of 10% on each. This sensitivity analysis is performed on the properties of a shaded kapton patch on a spherical, conducting, sunlit spacecraft subject to an ambient plasma environment which will produce large, negative potentials. Two main results are obtained: firstly, identification of the important role played by the high incident energy part of the secondary electron yield curve and secondly the ability of a low density, cold plasma component to limit negative charging.

GREAT BRITAIN (JCS)



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## 1 INTRODUCTION

Much effort has been expended in the development of software used to model the charging of spacecraft by magnetospheric plasmas[1]. Fully dynamic, three-dimensional codes are essential for determining the complex potential contours and differential potentials which develop around a spacecraft composed of many different surface materials in a complicated geometry. In order for such codes to give reliable results, it is essential that the basic interaction between the plasma environment and a given surface material is well understood.

By considering incident ion and electron currents to a surface (a function of the plasma environment and surface potential) and the secondary currents emitted from a surface (a function of the incident currents and surface material properties) it is possible to construct a simple numerical simulation to determine the equilibrium surface potential at which the net current to the surface is zero. Such a code may be used to assess the sensitivity of the solution to small changes in the input parameters which define the plasma environment and the surface material properties. The results of such a sensitivity analysis provide an estimate of the error bars on the results of more complex charging codes and also indicate where more accurate material data or plasma measurements must be made.

The EQUIPOT code has been developed to compute the equilibrium potential of a surface in a given plasma environment, and therefore provides an ideal framework for carrying out a detailed sensitivity analysis. This Memorandum gives a brief overview of the code and presents the results of a sensitivity analysis performed using the code. The scope of the analysis described here is limited to the study of a shadowed or partially illuminated kapton patch on a sunlit, conducting aluminium spacecraft structure. The environment chosen is a severe double maxwellian, with an additional component representing the cold plasma population. The results presented show the effects of small changes in the surface characteristics of kapton and the incident environment.

## 2 THE EQUIPOT CODE

The development of EQUIPOT is based on a number of requirements. These are described below, together with details of the code:

(i) *The basic geometry used by the code should be as simple as possible in order to allow modelling of differential charging.* EQUIPOT computes the equilibrium potential of a patch of dielectric material (or floating conductor) on an underlying spherical, conducting spacecraft. The solar illumination of

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the patch and the structure may be varied independently. The Debye sheath which develops around the patch may be set as either planar or spherical. The simple geometry used by EQUIPOT is shown in Fig 1. It is intended that the planar, or thin sheath approximation resulting from sheath limited collection is used in conjunction with LEO environments, where the Debye length is of the order of a few millimetres; the spherical or thick sheath approximation, resulting from orbit limited collection is more representative of the conditions which prevail in GEO where the Debye length is of the order of hundreds of metres, much larger than a typical spacecraft. Clearly, these two approximations represent limiting cases, realistic conditions will fall between these extremes, as shown in Fig 2. Following Ref 2, the currents considered are due to incident electrons, back-scattered electrons, incident ions, secondary electrons from incident electrons and ions, photo-emission and conduction. The latter involves the thickness and conductivity of an insulating material, or the thickness and conductivity of a dielectric substrate for an isolated conductor. The relative permittivity of the dielectric in each case affects the capacitance of the surface element and the resulting charging time.

(ii) *The numerical methods used throughout the code should be as simple as possible and run times should be consistent with an interactive code.* EQUIPOT uses a simple voltage stepping algorithm in order to determine the equilibrium potential. Mathematically, finding the equilibrium potential is a straightforward root-finding exercise; therefore it would be possible to employ fast and efficient algorithms to determine the solution. However, simply stepping the surface potential from an arbitrary starting point (usually 0 volts), computing the net current at each point until the solution is reached ensures that multiple root cases are handled properly, and also shows how each component of the net current changes as a function of surface potential. EQUIPOT also includes a facility to compute the current-voltage relationship for a surface between user defined potentials. Fig 3 shows the simple voltage stepping algorithm used by EQUIPOT.

(iii) *The environment definition should be as flexible as possible.* EQUIPOT accepts plasma environments as tables of measured particle spectra, single, double or triple maxwellian components, or combinations of all these. For example, if measured spectra are available for a given energy range, it is possible to append maxwellians which give realistic fluxes outside this range Alternatively, the environment may be defined entirely by maxwellian components. EQUIPOT splits the incident particle spectra into a series of monoenergetic 'swarms' and computes the net current due to each 'swarm'. Hence the speed and

accuracy of the simulation are functions of the number of equal logarithmic energy steps used to define the incident particle energy range (usually from 1 eV to twenty times the temperature of the hottest maxwellian component). In general, it has been found that 100 steps per integration give sufficiently accurate and quick results.

(iv) *Material properties should be defined in the standard NASCAP form.* Although EQUIPOT uses the same general format as NASCAP[3], there are some important differences. The properties of thickness, conductivity and dielectric constant relate to the insulating patch, or to the dielectric separating the floating conductor from the spacecraft structure. Hence, these values are input to the code separately from the normal material properties. Secondly, NASCAP replaces some of the input property values relating to secondary electron emission with re-computed values. Since EQUIPOT treats secondary electron emission (SEE) differently, this method is not adopted.

(v) *Emphasis should be placed on modelling the secondary electron emission yield function.* This plays a crucial role in the computation of equilibrium potential[4]. Hence EQUIPOT supports a number of different empirical and theoretical secondary electron emission yield models: these will be referred to as the 'Katz' model[1], the 'Whipple/Dionne' model[5] and the 'Sternglass' model[6]. EQUIPOT also supports normal or isotropic SEE yield functions.

(vi) *The code should be an interactive, 'engineering' tool.* EQUIPOT has been developed with a menu-driven user interface, pre-defined material and environment definition files and a continuously displayed panel indicating current set-up (*eg* floating and structure material type, integration step size, etc). For a given set of input parameters, the equilibrium potential is computed in a time of typically 1-2 minutes, allowing many permutations and combinations of parameters to be assessed at a single session.

## 3 SENSITIVITY ANALYSIS

### 3.1 Method

The analysis was performed assuming a kaption patch on a spherical, aluminium spacecraft. The structure is assumed to be sunlit, and therefore floats at a few volts positive. The surface properties of kapton are given below[7]:

Thickness : 25 μm
relative permittivity : 3.0
conductivity : 1.0E-15 mho/m
atomic number : 5.0
Max. normal SEE yield : 1.9
Energy at max normal SEE yield : 0.20 KeV
yield of 1 KeV protons : 0.455
energy at max proton yield : 140.0 KeV
photoelectron yield : 2.0E-3 $Am^{-2}$.

The sensitivity analysis computes the change in equilibrium potential as each parameter on this list is varied. Where appropriate, the input parameters are varied by 10% in each direction. The environment chosen for the study is a variation of the worst-case SCATHA environment[8], modified to give an equilibrium potential of -10.0 KV when applied to the definition of kapton given above. This provides a convenient datum which is used throughout the study, since the percentage change in the result is simply the amount that the equilibrium differs from -10.0 KV divided by 100. The double maxwellian environment with an additional cold plasma component is defined as follows:

$$Ne_1 = 0.9\ cm^{-3},\ Te_1 = 600.0\ eV$$
$$Ne_2 = 2.1\ cm^{-3},\ Te_2 = 26000.0\ eV$$
$$Ne_3 = 0.1\ cm^{-3},\ Te_3 = 1.0\ eV$$
$$Ni_1 = 1.0\ cm^{-3},\ Ti_1 = 350.0\ eV$$
$$Ni_2 = 0.7\ cm^{-3},\ Ti_2 = 25000.0\ eV$$
$$Ni_3 = 0.1\ cm^{-3},\ Ti_3 = 1.0\ eV\ .$$

This differs from the SCATHA worst case environment in two ways; firstly a low density, cold plasma component has been added and secondly the electron and ion densities of the 'hot' component have been adjucted to give the required equilibrium potential.

It should be noted that the equilibrium potential of -10.0 KV obtained with the data shown above used the Katz model of secondary electron emission and assumed isotropic particle incidence. The time taken for the kapton to reach this equilibrium potential was 4.0 hours.

### 3.2 Variation of parameters affecting the conductivity current

The thickness of kapton and its conductivity affect the conduction current to the structure and hence the equilibrium potential. Fig 4 shows how the equilibrium potential, $V_E$ varies as the thickness of kapton is increased from

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5 μm to 200 μm. At thicknesses above 50 μm, $V_E$ is relatively insensitive to changes in thickness, whilst below this value, changes in thickness cause major changes in $V_E$ . Fig 5 shows how $V_E$ varies for 25 μm kapton as bulk conductivity ranges from 1.0E-14 to 1.0E-16 mho/m. The significant change resulting from making kapton slightly more conductive 's evident.

### 3.3 Variation in the photoelectric yield current

It is instructive to illuminate the kapton patch at oblique angles of incidence. EQUIPOT allows the cosine of the sun angle to be input, where 1.0 represents normal solar incidence. Fig 6 shows how $V_E$ is affected by the variation of illumination angle from complete shadow (90.0°) to near 72° when negative charging is completely prevented by the current of photoelectrons.

### 3.4 Variation of SEE current for isotropic particle incidence

An isotropic flux tends to increase the value of the maximum secondary electron emission yield and moves its position to a higher energy[5]. Two of the secondary electron emission yield models supported by EQUIPOT (the Katz and Whipple/Dionne expressions) include an expression which corrects for isotropic incidence. The positions of the peaks in the corrected models are shown in Table 1 and the full SEE curves are shown in Fig 7. Although the peak positions are in good agreement, the main difference between the curves is apparent at high incident energies where the Whipple/Dionne expression gives a much higher yield.

Table 1

Parameters defining the isotropic SEE yield function

| SEE model | $d_{MAX}$ | $E_{MAX}$(eV) |
|---|---|---|
| Katz *et al*, 1977 | 2.74 | 338.0 |
| Whipple, 1981 | 2.77 | 338.0 |

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Table 2

Results of variations in the isotropic Katz expression

| Variation | $d_{MAX}$ | $E_{MAX}$(eV) | $V_E$(V) |
|---|---|---|---|
| Default | 2.740 | 338.0 | -10000 |
| $d_{MAX}$ + 10% | 3.014 | 338.0 | -9879 |
| $d_{MAX}$ - 10% | 2.466 | 338.0 | -10152 |
| $E_{MAX}$ + 10% | 2.740 | 371.8 | -9998 |
| $E_{MAX}$ - 10% | 2.740 | 304.2 | -10004 |

Table 2 shows the results of varying the maximum yield and its position for the (isotropic) Katz expression by 10% in both directions. Since only the position of the peak is being changed by small amounts, and the shape of the high energy tail of the distribution changes very little, the equilibrium potential is affected only slightly (less than 2%).

Table 3 shows the results of a similar analysis performed using the Whipple/Dionne expression. Two points are evident: firstly the absolute equilibrium potential is only -2.8 kV, significantly different from the results obtained with the Katz model, and secondly, $V_E$ is much more sensitive to small changes in the peak position. Once again, it is the high incident energy tail of the distribution which gives a much higher yield than the Katz expression, and is much more sensitive to changes in the peak position.

Table 3

Results of variations in the isotropic Whipple/Dionne expression

| Variation | $d_{MAX}$ | $E_{MAX}$(eV) | $V_E$(V) |
|---|---|---|---|
| Default | 2.770 | 338.0 | -2805 |
| $d_{MAX}$ + 10% | 3.047 | 338.0 | 0 |
| $d_{MAX}$ - 10% | 2.493 | 338.0 | -4130 |
| $E_{MAX}$ + 10% | 2.770 | 371.8 | -2257 |
| $E_{MAX}$ - 10% | 2.770 | 304.2 | -3327 |

It is not intended that these results make any statement about the applicability of various SEE models, but they provide a clear illustration that the choice of SEE model is critical. In particular, they demonstrate the importance of correctly modelling the high incident energy tail of the SEE yield function.

### 3.5 Variation in SEE current for normal particle incidence

It is instructive to repeat the calculations of the previous section for SEE yield functions based on normal particle incidence. It should be noted that the expression for backscattered electrons is also corrected for normal incidence. For this case, EQUIPOT also supports the commonly used Sternglass expression as well as the normal versions of the Katz and Whipple/Dionne expressions. Fig 8 is a plot of the three functions. By definition, all three curves share the same peak position although it is once again evident that the main difference occurs at high incident energies. Table 4 shows the results of small (10%) movements of the position of the peak on equilibrium potentials obtained with each of the three expressions. For the Katz yield function, changing to normal incidence has reduced the total secondary yield, such that the equilibrium potential is now near −15 kV. Both the Katz and Sternglass expressions are relatively insensitive to moving the location of the peak, in fact, small changes in the energy of the peak have almost no effect. Changing the maximum yield by 10% induces changes of less than 1% in the equilibrium potential. $V_E$ computed with the Whipple/Dionne expression changes by almost 4% for 10% changes in the position of the peak.

Table 4

Results of varying the normal SEE function

| Variation | $d_{MAX}$ | $E_{MAX}$(eV) | SEE function | | |
|---|---|---|---|---|---|
| | | | Katz $V_E$ | Whipple $V_E$ | Sternglass $V_E$ |
| Default | 1.90 | 200.0 | −15008 | −11913 | −15642 |
| $d_{MAX}$ + 10% | 2.09 | 200.0 | −14941 | −11463 | −15640 |
| $d_{MAX}$ − 10% | 1.71 | 200.0 | −15075 | −12337 | −15644 |
| $E_{MAX}$ + 10% | 1.90 | 220.0 | −15007 | −11765 | −15637 |
| $E_{MAX}$ − 10% | 1.90 | 180.0 | −15009 | −12068 | −15647 |

As observed for isotropic incidence, the equilibrium potential is much more sensitive to changing the secondary yield model rather than changing the peak position for any single model.

### 3.6 Changes in the current of backscattered electrons

The model used for the backscattered electron yield is that described by Whipple[5]. The yield is a function of the atomic number of the surface material and also whether particles are incident normally or isotropically. EQUIPOT uses the isotropic correction automatically if the SEE yield function is chosen as isotropic, hence effects of the different backscatter coefficient for normal or isotropic incidence are included in the analysis of the secondary electron yield function. Therefore the atomic number provides the only parameter which might sensibly be varied over a limited range in order to investigate changes in the energy dependent backscatter coefficient. The results are shown in Table 5 and demonstrate that the effect of changing $Z$ is small (less than 1% for 10% changes in $Z$ ).

Table 5

Result of small changes in Z

| Variation | Z | $V_E$(V) |
|---|---|---|
| Default | 5.0 | -10000 |
| Z + 10% | 5.5 | -9933 |
| Z - 10% | 4.5 | -10077 |

### 3.7 Changes in the secondary electron current due to ion impact

The yield function used is that described by Whipple[5] and is defined by two parameters; the yield for incident 1 KeV protons, and the energy at the maximum yield. The results of varying these parameters by 10% are shown in Table 6. All resulting changes in $V_E$ are less than 5%. However, it is interesting to note the effect of neglecting this current component; the equilibrium potential approaches -21 KV.

Table 6

Effect of varying SEE due to ion impact

| Variation | Yield (1 KeV) | $E_{MAX}$ (KeV) | $V_E$(V) |
|---|---|---|---|
| Default | 0.455 | 140.0 | -10000 |
| Yield at 1 KeV + 10% | 0.501 | 140.0 | -9604 |
| Yield at 1 KeV - 10% | 0.410 | 140.0 | -10483 |
| Max yield energy + 10% | 0.455 | 154.0 | -9965 |
| Max yield energy - 10% | 0.455 | 126.0 | -10049 |
| No SEE due to ions | | | -20797 |

### 3.8 Changes in the definition of the plasma environment

Finally, it is important to assess the effects of making small changes in the density and temperature of the maxwellian components used throughout this study. Firstly, the effect of the cold plasma added to the severe SCATHA environment must be investigated. A density of 0.1 $cm^{-3}$ is too small to be measured, the effects of both removing it completely and also increasing it are summarised in table 7. This is a very significant result and shows how the presence or absence of cold plasma at GEO can significantly affect spacecraft charging.

Table 7

Effect of varying the thermal ion density

| Variation | Ni ($cm^{-3}$) | Ti (eV) | $V_E$(V) |
|---|---|---|---|
| Thermal ions absent | 0.0 | 1.0 | -16056 |
| Default | 0.1 | 1.0 | -10000 |
| Increased density | 0.2 | 1.0 | -7829 |

Table 8 shows the results of varying the density and temperature of the two main electron and ion plasma components by 10%. The colder (600 eV) electron component does not contribute to the current balance when the spacecraft potential exceeds several thousand volts negative, hence, as observed, it has no effect on

a spacecraft equilibrium potential of around -10 KV. Changing the temperature and density of the 'hot' electron component results in changes of less than 8% in $V_E$ , whilst similar changes in the 'hot' ion component give rise to changes in $V_E$ of less than 1%. It is interesting to note that an increase in the temperature of the 'hot' ion component makes $V_E$ less negative, whilst increasing the temperature of the cold component has the opposite effect, although both changes are small (less than 1%).

Table 8

Effect of varying plasma density and temperature

| Variation | $V_E$(V) |
|---|---|
| Default | -10000 |
| $Ne_2$ + 10% | -10651 |
| $Ne_2$ - 10% | -9362 |
| $Ni_2$ + 10% | -9925 |
| $Ni_2$ - 10% | -10082 |
| $Te_2$ + 10% | -10721 |
| $Te_2$ - 10% | -9282 |
| $Ti_2$ + 10% | -9975 |
| $Ti_2$ - 10% | -10032 |
| $Ne_1$ + 10% | -10000 |
| $Ne_1$ - 10% | -10000 |
| $Ni_1$ + 10% | -9818 |
| $Ni_1$ - 10% | -10225 |
| $Te_1$ + 10% | -10000 |
| $Te_1$ - 10% | -10000 |
| $Ti_1$ + 10% | -10085 |
| $Ti_1$ - 10% | -9911 |

## 4 CONCLUSIONS

Although the scope of this study is limited to a single material in a single type of environment, it has yielded some valuable results. Two main features have emerged; the importance of correctly modelling the high incident energy part of

the secondary electron emission yield function and the importance of the role played by a cold plasma population.

The temperature of the 'hot' electron population (25 KeV) chosen for this study corresponds to a position on the SEE yield curve of between 75 and 125 times the energy of the yield peak. It is at these energies, where the yield is less than 0.2, where various models disagree. Further SEE yield measurements at high incident energies are necessary to resolve this problem. It may be more sensible for codes such as EQUIPOT to use direct SEE yield data, rather than rely on an empirical relationship.

Since thermal ions are rarely completely absent from the geostationary plasma environment, particularly during prolonged geomagnetically quiet periods, it is essential to include their effect in any charging simulation.

EQUIPOT has proved to be a very flexible tool in performing this type of analysis. Future studies are proposed which include investigation of the behaviour of materials in measured geostationary plasma environments with a view to explanations of the 'eclipse' and 'barrier' charging events observed on the Meteosat-2 spacecraft[9].

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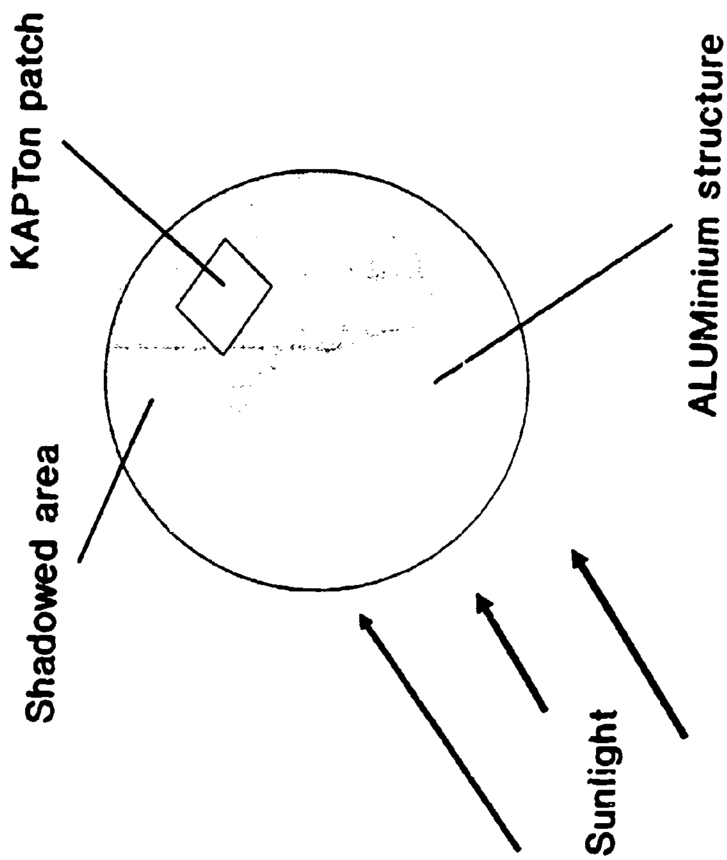


Fig 1 Schematic showing the geometry used by EQUIPOT

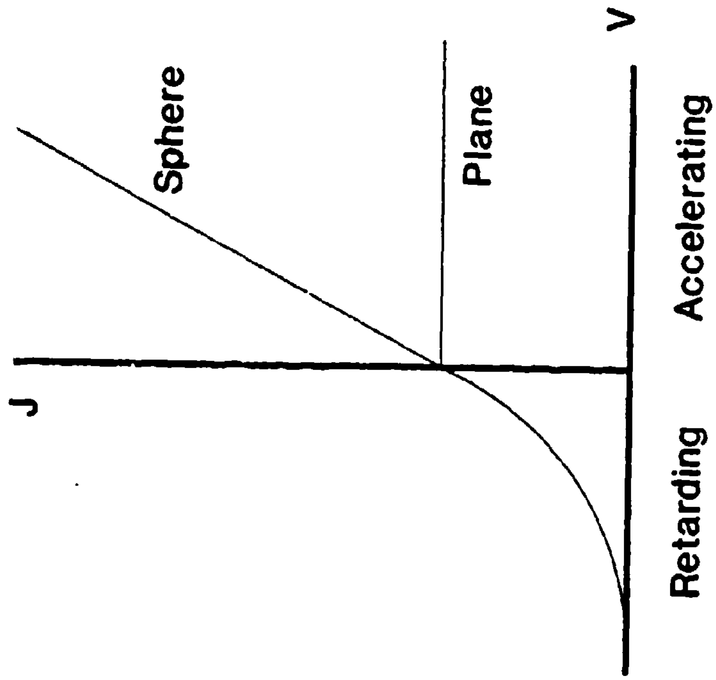


Fig 2 Effect of geometry on a probe current-voltage characteristic

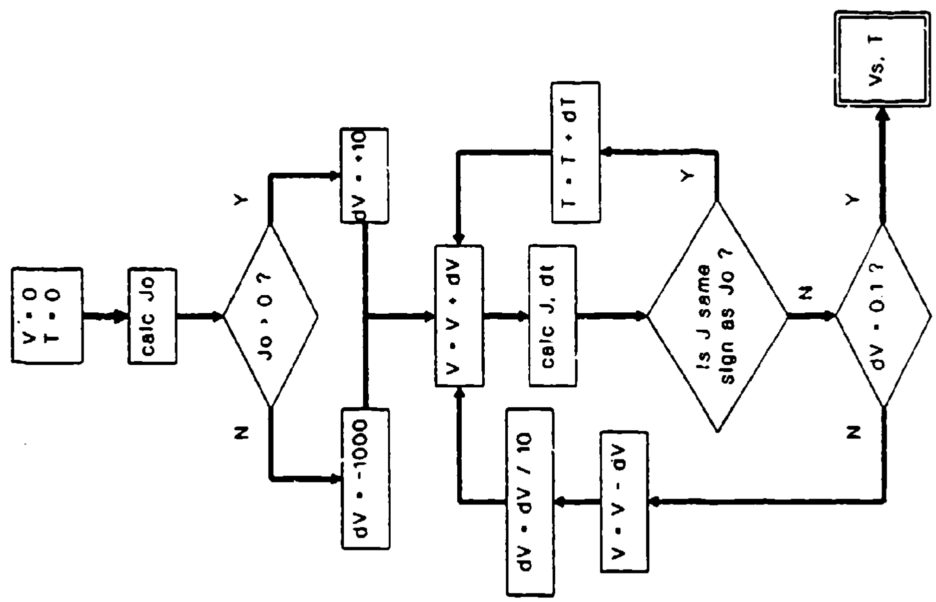


Fig 3 Voltage stepping algorithm used by EQUIPOT

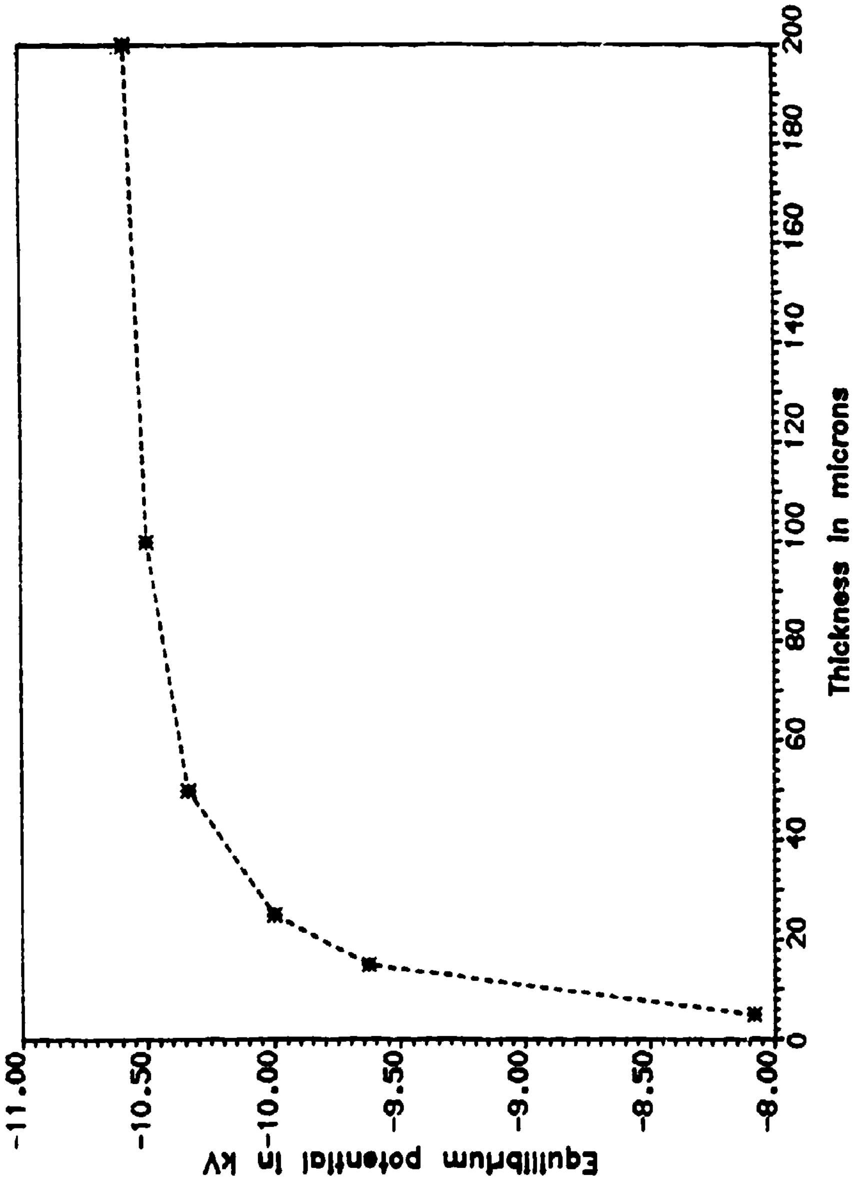


Fig 4 Equilibrium potential as a function of kapton thickness

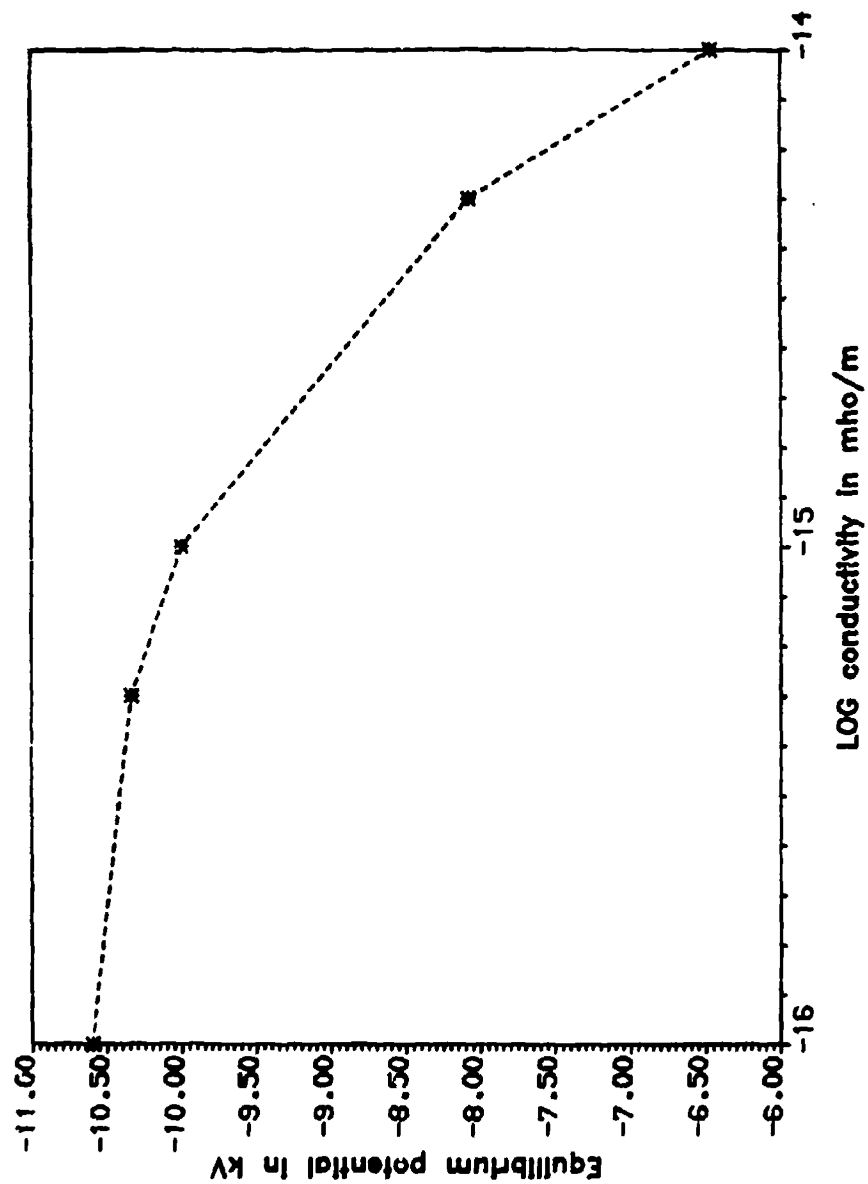


Fig 5 Equilibrium potential as a function of the bulk conductivity of kapton

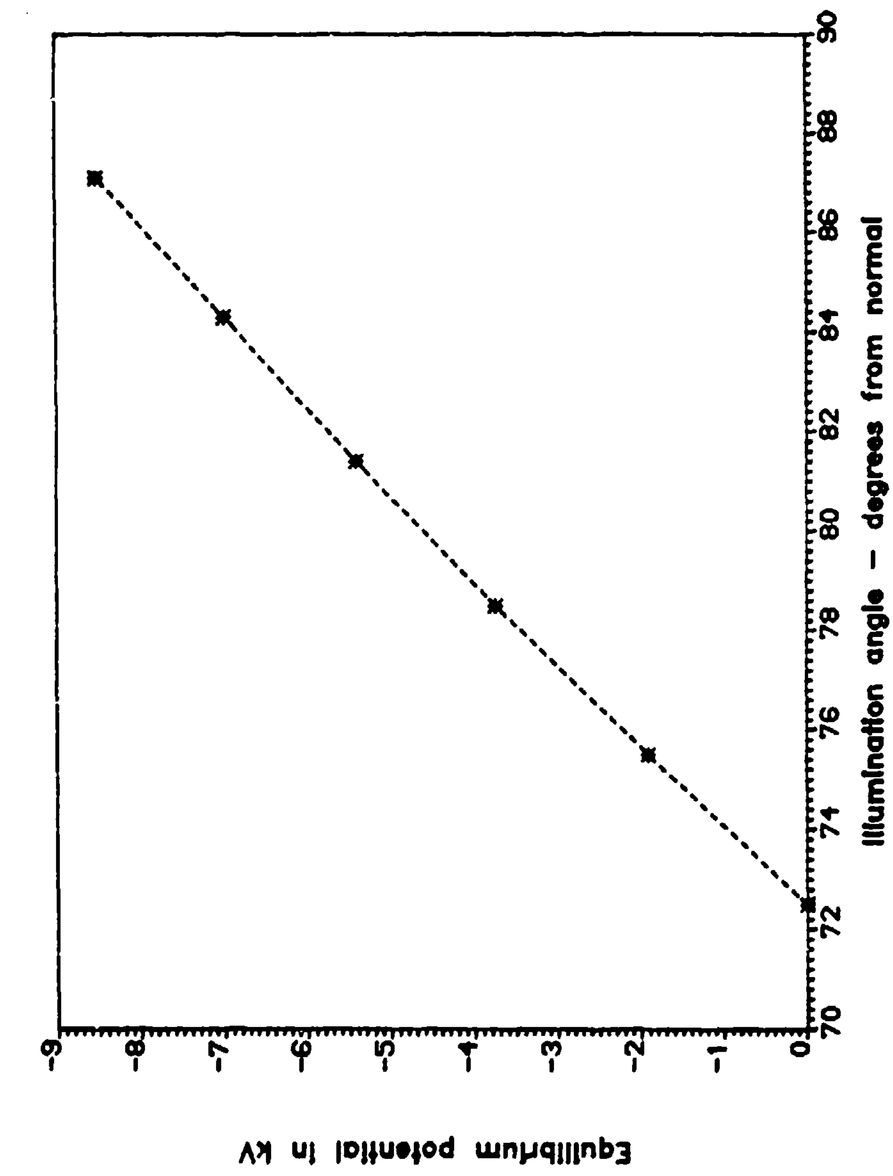


Fig 6 Equilibrium potential as a function of illumination angle for a kapton surface

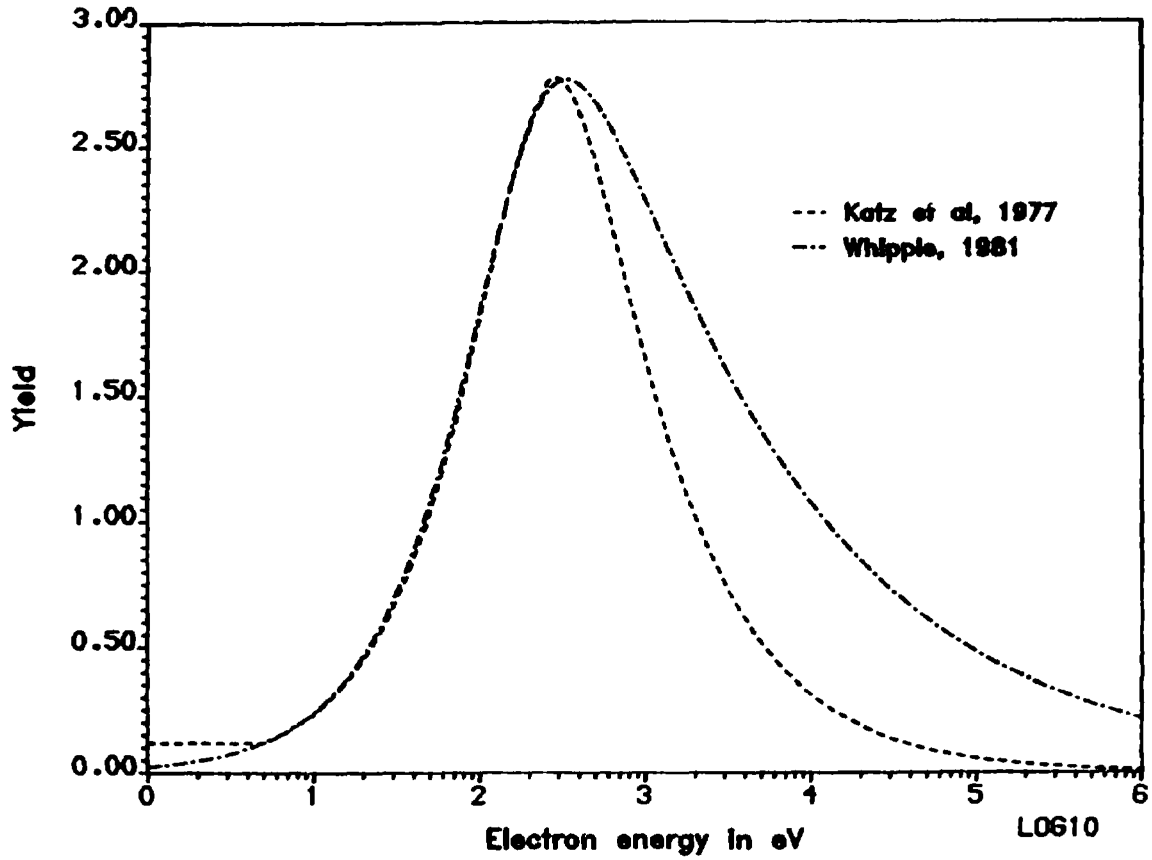


Fig 7 Secondary electron yield for kapton; isotropic particle incidence

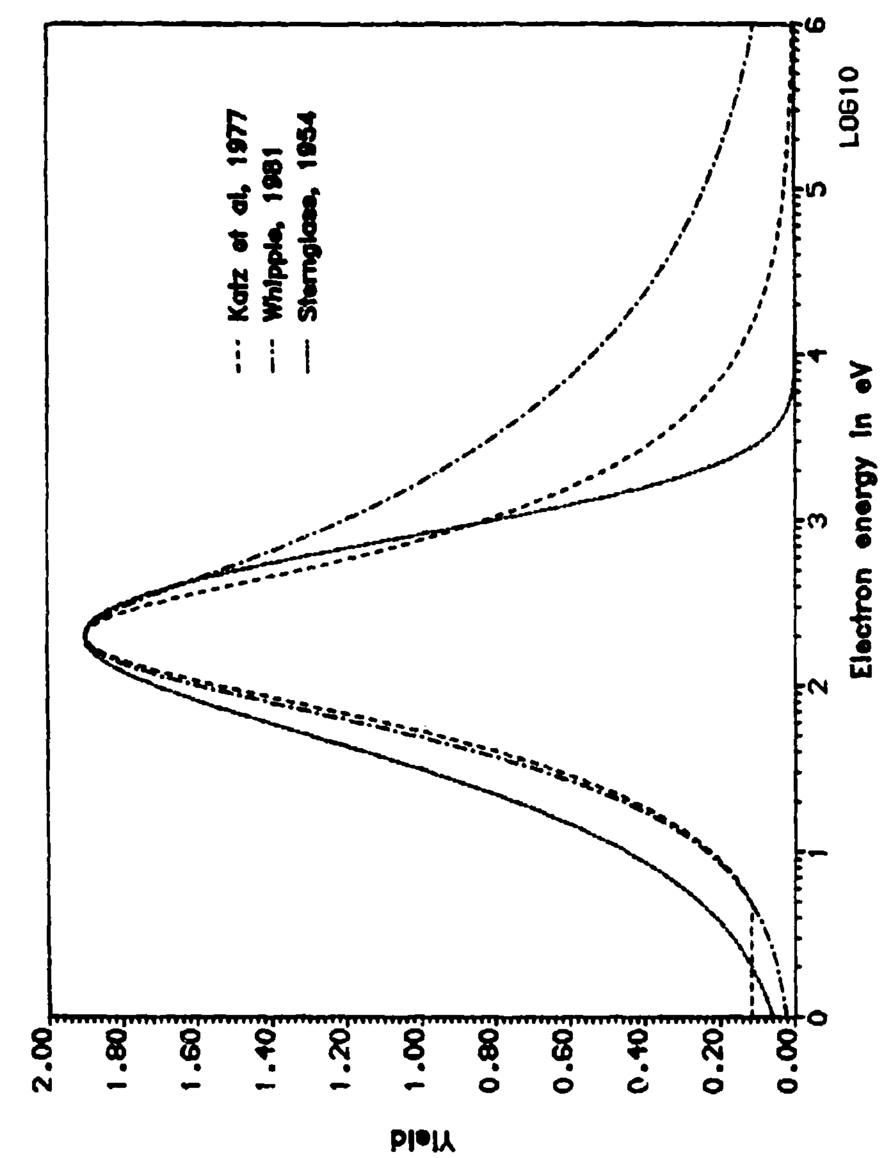


Fig 8 Secondary electron yield for kapton; normal particle incidence

# REPORT DOCUMENTATION PAGE

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17. Abstract

Computer simulation techniques using codes such as NASCAP have proved very successful in tackling the spacecraft charging problem. Although a full dynamic three-dimensional code is required to model a spacecraft in orbit, simpler codes (*eg* MATCHG) can do much to clarify the interaction between the environment and a surface. It is difficult to obtain complete data on either the incident particle fluxes or the material properties which determine the various current components. The latter are dependent upon particle energy which is in turn a function of surface potential; therefore the resulting equilibrium and the charging time to attain this potential are controlled by a long list of input parameters. In order to assess the sensitivity of a solution to each of these inputs, a simple code (EQUIPOT) is used to calculate the net current as surface potential is stepped form zero to that required for equilibrium (Jnet = 0). The required accuracy for all the parameters is then established by successively introducing a delta of 10% on each. This sensitivity analysis is performed on the properties of a shaded kapton patch on a spherical, conducting, sunlit spacecraft subject to an ambient plasma environment which will produce large, negative potentials. Two main results are obtained: firstly, [illegible] the important role played by the high incident energy part of the [illegible] curve and secondly the ability of a low density, cold [illegible] negative charging.